

# **A multivariable model for estimation of vapor cloud explosion occurrence possibility based on a Fuzzy logic approach for flammable materials**

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## **Abstract**

In this paper, a new method based on Fuzzy theory is presented to estimate the occurrence possibility of vapor cloud explosion (VCE) of flammable materials. This new method helps the analyst to overcome some uncertainties associated with estimating VCE possibility with the Event Tree (ET) technique. In this multi-variable model, the physical properties of the released material and the characteristics of the surrounding environment are used as the parameters specifying the occurrence possibility of intermediate events leading to a VCE. Factors such as area classification, degree of congestion of a plant and release rate are notably affecting the output results. Moreover, the proposed method benefits from experts' opinions in the estimation of the VCE possibility. A refrigeration cycle is used as the case study and the probability of VCE occurrence is determined for different scenarios. In this study, sensitivity analysis is performed on the model parameters to assess their effect on the final values of the VCE possibility. Furthermore, the results are compared with the results obtained using other existing models.

**Keywords:** Vapor Cloud explosion (VCE), Probability, possibility estimation, Fuzzy algorithm, Event tree.

## 1. Introduction

Events caused by the catastrophic release of a flammable substance in the surrounding environment, such as a storage tank rupture or a hole in a pipe, can lead to a variety of outcomes. The occurrence of these outcomes depends on factors such as operating conditions of the source, type of released material and surrounding conditions. Events such as pool fire, fire ball, Vapor Cloud Explosion (VCE), flash fire, and BLEVE are some of the possible outcomes.

Vapour cloud explosions (VCEs) are a major hazard in industrial plants where large amounts of flammable materials are stored or processed. In the last few decades, several VCEs have occurred in process plants resulted in almost total destruction of the those plants (Sharma et al.,2013). Several studies about past accidents indicate the importance of VCEs (Abdolhamidzadeh et al., 2011; Sharma et al., 2013; Salzano and Cozzani, 2005). Today, Quantitative Risk Assessment (QRA) has become an efficient tool in decision making for safety and process experts. To assess the risk of any accident scenario, it is necessary that the probability of that event be determined in addition to estimating the probable consequences. Event tree analysis is known to be a standard tool for calculating the frequency of incident outcomes. However, the existence of many effective and sometimes neglected parameters cause uncertainties in the calculations of event frequencies. A better understanding of the influencing factors for each accident scenario will lead to a more precise estimation of event frequencies. Several studies on uncertainties in event trees have been performed which indicate the importance of this tool for incident frequencies' estimation ([A. Neri](#) et al., 2008; [Umit Catalyurek](#) et al., 2010; [Julwan Hendry Purba](#), 2014)

For instance, while developing conventional event trees, the type of released material does not play a role in determining the intermediate probabilities that build the overall structure on the event tree. Nonetheless, it is proven in several studies such as Abdolhamidzadeh *et. al.* (2011) that the type of material has a significant effect on the outcome of an event tree.

Badri *et al.* (2013) proposed a model based on event tree analysis to calculate the vapor cloud explosion frequency, in which they have tried to consider the effect of various parameters influencing the frequency of events. Their idea was to convert the unit into subsets such that the material properties and operating conditions in each specific subset are constant and for each

subset, the VCE frequency is calculated and finally the frequencies of all subsets are added together.

Wiekema(1984) analyzed VCEs in past accidents and tried to determine the effect of parameters such as the amount of released material, the ignition duration, reactivity of released material on the VCE occurrence probability. But there are different parameters affecting the occurrence mechanism and probability of VCEs. Some of these parameters are well established and embedded in the existing models for prediction of VCE occurrence, while some other factors are frequently missing in the evaluations.

In problems where there is ambiguity and uncertainty about the influencing parameters, the opinion of an expert on the parameters influencing the event tree, which is based on knowledge of the circumstance, process and past events, can make the model more accurate. One of the drawbacks of the existing models for VCE probability estimation is that the expert vision cannot be intervened.

In this research mathematical models based on the theory of accidents occurrence, data from past events and experiences of experts are all integrated in order to provide a comprehensive model for estimation of VCE probability. For this purpose, a Fuzzy algorithm, as an efficient mathematical model for problems in which there isn't a complete understanding in parameters dependence and there is no parameter certainty on the issue, is used.

Some recent research has been performed on using Fuzzy set theory in different safety analyses. For instance Markowski *et al* (2007) proposed a method for analyzing layers of protection against explosion (EXLOPA) based on Fuzzy algorithm. Forming Fuzzy sets associated with different factors affecting the explosion in any protection layer, they presented their model and finally compared their model results with the previous model results. Huang and Wang (2001) have proposed a model based on the Fuzzy logic for event-tree analysis. Their main aim was to include human error into event-tree by using Fuzzy concepts. Yuhua and Datao (2005) presented a model based on Fuzzy set theory to detect pipe failure probability based on fault tree model. They tried to gather the probability of early events together and obtain more accurate answers compared with the previous models, by combination of expert opinion and Fuzzy theory. Markowski and Mannan (2009) present the application of Fuzzy logic for risk assessment of

accident scenario expressed by fault and event tree combined in the “bow-tie” approach. Mure and Demichela (2009) uses Fuzzy logic in the procedure proposed to quantitatively assess the risk of occupational accident for different industrial and site activities and to identify the most efficient intervention measures that can be taken to reduce risk.

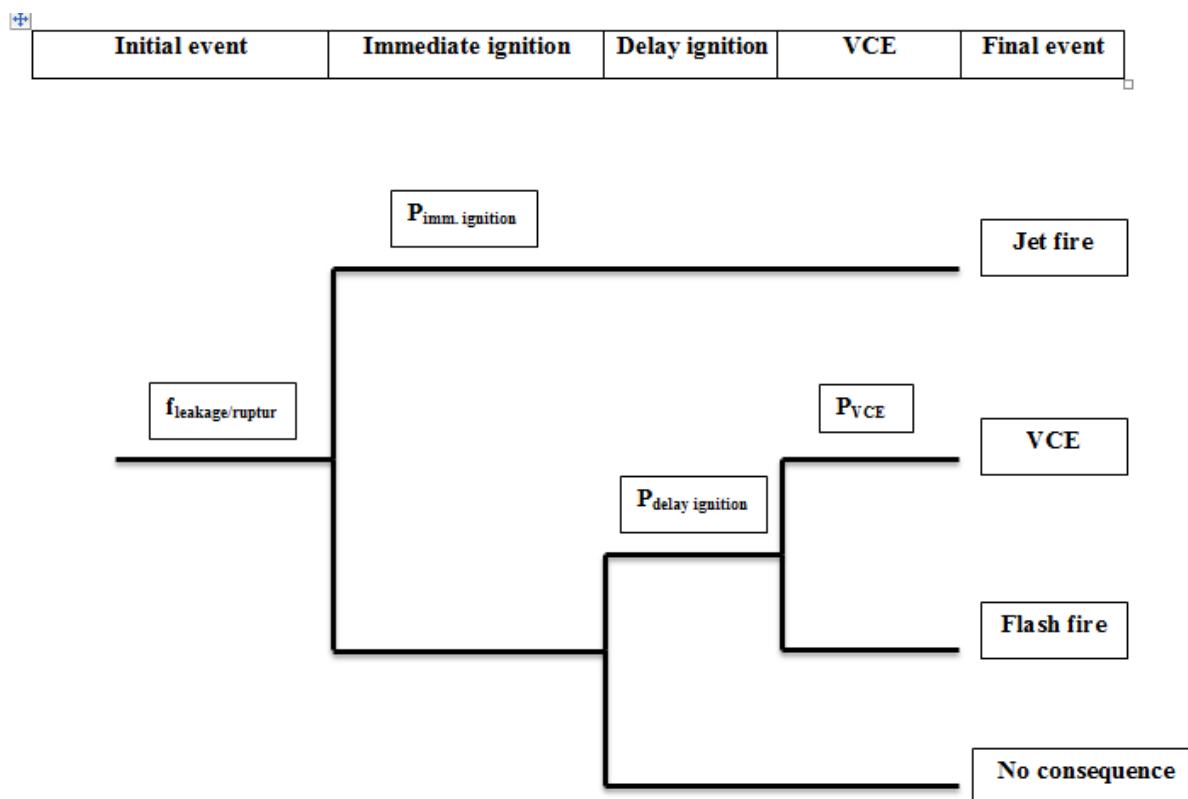
In general, the use of fuzzy logic in various applications, including safety, is performed in two ways: first when there is uncertainty in the data or information (subjective uncertainties), hence, in case that the limit and certainties of numbers are not clear. Secondly, fuzzy logic is employed when there is uncertainty in the model (objective uncertainties), that is, when the relationship between the variables is not entirely clear. Fuzzy logic, with the help of variability, according to available data, as well as the empirical and theoretical relationships in the past and the experience of experts, and by creating fuzzy rules in the form of IF-THEN conditions, specifies the relationship between the independent and dependent variables. In the field of process safety, a variety of articles regarding this application of fuzzy logic has been developed recently (Markovski et al., 2011; Gentile et al., 2003; Markovski and Mannan, 2008)

The main advantage of the proposed Fuzzy model is that it has high flexibility in applying an expert opinion in forming effective dependencies in event-tree. In this case it is not permissible to use the term probability; instead the term possibility should be used; because the probability of an event in a variety of experimental conditions tends to unity. In this case, however, since the expert opinion, social, economic, management and other conditions are included, various possibilities can be achieved based on different condition (Zimmermann, 2001).

In this new approach, instead of having several scenarios and consequently several event-trees, a general event-tree is introduced for which, considering operating and surrounding conditions and also the type of released material, the frequency of each of the event scenarios can be achieved. Finally, a sensitivity analysis is performed on the model, so that the effect of certain factors such as the type of released material and environmental conditions (humidity, ambient temperature, unit type, etc.), is examined.

## **2. Event tree calculations**

Having the frequency of a catastrophic release as the initiating event, Event Tree is used for calculating the frequency of different possible outcomes. Upon a flammable chemical release, these outputs can be pool fire, jet fire, VCE, VCF and BLEVE. Figure 1 shows a typical Event Tree developed for a flammable vapor release:



**Figure 1. Event Tree developed for a flammable vapor release**

For calculation of each branch frequency in an event tree, the following parameters shall be specified:

### 2.1. Initial event frequency

For specifying the frequency of initial event, using failure frequency databanks which are constructed based on past accident records, is quite common. There are several databanks available such as API 581 (2008), OGP (2010b), Handbook failure frequencies (*LNE, 2009*), and methods for adjusting failure rates based solely on the thickness of the equipment relative to typical industry practice (Thomas, 1981) .

**Tab. 1.** default equipment frequency (Moosemiller, 2011)

Equipment type	Leak frequency(per year except as noted				Notes
	1/8"-1/2" hole	1/2"-2" hole	2"-8" hole	rupture	
Process pipe	3E-6/(D <sub>p</sub> -D <sub>h</sub> ) D <sub>p</sub> =pipe diam (in), D <sub>h</sub> =pipe hole (in)				Frequency is per foot of pipe length per year
Pressure vessel	2E-4	1E-4	1E-5	1E-5	
Atoms tank	5E-3	1E-3	1E-4	2E-5	
Compressor, centrifugal	5E-3	1E-3	-----	3E-5	
Heat exch, shell	1E-3	2E-4	4E-5	2E-5	

## 2.2 Probability of immediate ignition

As it is shown in Figure 1, after a release, the outcome can be different based on the presence or absence of an immediate ignition source. Presence of an immediate ignition source will lead to formation of a jet fire, while lack of any immediate ignition source will let the released material to form a cloud. So one of the key parameters in calculating an Event Tree, is specifying the probability of immediate ignition. Different values are reported in literature (Bond, 1991. Bevi, 2009; Uijt de Haag and Ale, 2005). Many of these available values are fixed quantities independent of release rate or nature of chemical which is released.

Moosemiller (2011) proposed an equation in terms of the auto ignition temperature, the ambient temperature, operation pressure and the minimum ignition energy, based on which probability of immediate ignition is calculated (equation 1).

$$P_{imm.ignition} = \left( 1 - 5000e^{-9.5\left(\frac{T}{T_{Auto\ ignition}}\right)} \right) + \left[ 0.0024 \times \frac{P^{\frac{1}{3}}}{MIE^{\frac{1}{3}}} \right] \quad (1)$$

Where  $T_{Auto\ ignition}$  and T are in degrees Fahrenheit, P is in psig, and MIE is in mJ.

## 2.4 Probability of delayed ignition

When ignition does not occur immediately, and there is sufficient time to form a vapor cloud, then a delayed ignition may happen. External sources of required energy for the ignition can be rotary equipment, furnace, heat exchangers, flare, vehicles, etc. Similar to immediate ignition,

different values are reported for probability of delayed ignition (OGP, 2010a; Bevi, 2009). Spencer and Rew (1997) proposed an exponential model to calculate delayed ignition probability and Moosemiller corrected this model (Equation 2).

$$P_{\text{delayed ignition}} = 1 - ke^{-at} \quad (2)$$

In this relationship, “k” is a ‘strength constant’ and is related to presence of ignition source in the release area, “a” is a ‘time constant’ and estimated based on data collected or derived by empirical equations. Table 2 shows the probability of delayed ignition in one minute for various ignition sources. As it can be seen in Equation 2, factors such as the number and distance of ignition sources from the release point which theoretically influence the probability of delayed ignition, are neglected here.

**Tab. 2.** probability of ignition in one minute for various ignition source type (Uijt de Haag and Ale, 2005)

Source type	Source	Probability of ignition in one minute
If the flammable cloud size is known:		
Point source	Flare	1
	Fired exchanger	0.3
	Boiler	0.9
	Motor vehicle	0.9
Line source	High power electrical line	0.001 L (L= length of line covered by cloud in feet)
Area source	Roadway	1-0.7 <sup>V</sup> (V=average number of vehicle covered by cloud)
	Process plant	F (F= fraction of process unit covered by cloud)
	Residential population	1-0.99 <sup>N</sup> (N=number of people covered by cloud)
If the flammable cloud size is unknown:		
	High equipment density	0.5
	medium equipment density	0.25
	low equipment density	0.1
	confined space with- no equipment	.02

## 2.5 Probability of Vapor Cloud Explosion (VCE)

Upon presence of a delayed ignition source, two different outcomes may happen: VCE or vapor cloud flash(VCF). In case of release, in a congested area or release of significant amount of flammable gas, a VCE is more probable to happen. On the other hand, when gas is released in open area or the amount of released gas is not that much, a VCF will probably occur. The consequences of these two events are significantly different. In addition to degree of congestion and inventory of released material, other factors such as nature of the released chemical are influencing the probability of VCE or VCF. But the available recommended values or formulas to predict these probabilities often neglect some of these key factors (AIChE/CCPS, 1994).

Cox, Lees and Ang developed a relationship upon which the occurrence probability of VCE can be determined in terms of the released material rate (Equation 3) (Lees, 1996).

$$P_{VCE} = .024 m'^{0.435} \quad (3)$$

Where  $m'$  is material release rate in lbs/sec in the above equation.

By multiplication of the initial event frequency and occurrence probabilities in each branch, the final events frequency can be calculated in Event Tree. Equation 4 shows how the frequency of a VCE as a final outcome can be calculated according to the event tree expanded in Figure 1.

$$f_{VCE} = f_{leakage} \times P_{delayed\ ignition} \times (1 - P_{imm.ignition}) \times P_{VCE} \quad (4)$$

Where  $f_{leakage}$  is leakage frequency in 1/year,  $P_{delayed\ ignition}$ ,  $P_{imm.ignition}$  and  $P_{VCE}$  are delayed ignition, immediately ignition and VCE/VCF probabilities.

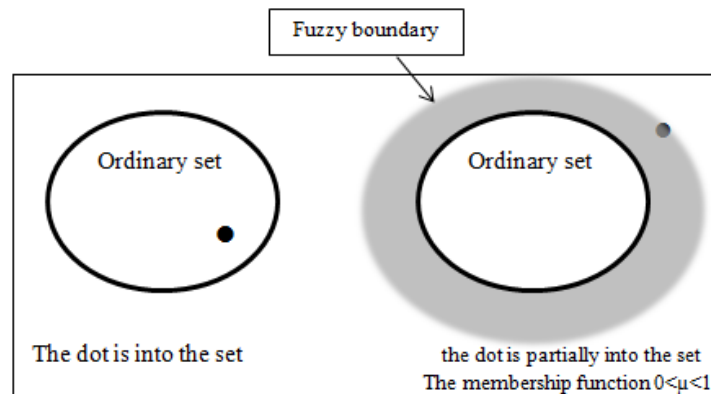
As it was mentioned above in specifying each of the probabilities in Equation 4, there are several uncertainties and also some of the available formulas are neglecting some of the key factors. To overcome these deficiencies, a new method based on Fuzzy theory is proposed to increase the precision in calculating VCE frequency in a plant.

### 3. Proposed method for event tree calculation



### 3.1 Fuzzy theory

Fuzzy logic or possibility theory is an effective tool for dealing with problems of which their boundaries or definitions are not completely known. The theory of Fuzzy logic is somehow in conflict with probability theory (the Boolean theory). In Boolean theory, an element can be a member of a specified set or not, but in Fuzzy theory, an element can be defined as a partial or general member of a set (Yen and Langari, 1999). The position of a member in Fuzzy theory is determined by the membership function ( $\mu$ ), by which the 'degree of belonging' to a certain set is identified with a number between 0 and 1 ( $0 < \mu < 1$ ). If the degree of belonging is zero, it means that an element is not completely a member of a set; and if it is unity, it means that it is wholly belongs to a specific set. Figure 2 shows the different concepts of the Boolean and Fuzzy theory.



**Figure 2.** difference between ordinary sets and Fuzzy sets

The membership function ( $\mu$ ) in safety and reliability analysis is defined by the typical convex functions of triangular, trapezoidal and Gaussian type. In this paper triangular membership function is applied. because this type of membership function is the one of the most common choice for safety systems(shahriar et al., 2012). To determine the relationship between the Fuzzy set, so-called Fuzzy rules should be built. For the formation of Fuzzy rules and the corresponding Fuzzy functions, experts' opinion and also existing evidences, based on past data, have a significant

effect. The number of Fuzzy rules must be such, that they encompass all the desired function space. Equation 5 shows the structure of a Fuzzy rule as an example.

$$\text{if } x \text{ is } x_i' \text{ and } y \text{ is } y_j' \text{ and } z \text{ is } z_k' \text{ then } w \text{ is } w_m' \quad (5)$$

Where  $x, y, z$  are independent variables,  $w$  is dependent variable which are quantitative,  $x_i', y_j', z_k'$  and  $w_m'$  are linguistic variables.

fuzzy rules in the form of if-then should be created so that all the problem space can be covered qualitatively. To do so, in this paper, a combination of experts experiences and past data in the form of questionnaires in several stages were used.

In the first stage, it is important to prioritize the variables at each node of the event tree. To prioritize these variables, questionnaires in the form of paired comparisons were produced and after collecting data of elites, they were analyzed in the super decision software. Due to the super-matrix created by the software, and also considering a minimum degree of importance for variables in each node, prioritization of variables based on internal relations are specified and variables are selected based on their degree of importance. The effect of available relationships and data were considered in this decision.

In the second stage, fuzzy rules are determined. Based on the prioritization of the criteria at each node and their importance in the former stage, some questionnaires are prepared, in which the prioritization and the importance degree of every sub-criteria, which are fuzzy sets, is determined. Finally, by using paired comparisons and super decision software, sub-criteria prioritization of every variable is done. Taken all the variables sub-criteria in each rule together, a decision is made to determine the fuzzy rules.

These linguistic variables are those qualitative variables which are used to transform the quantitative ranges of independent variables to qualitative expressions. For each independent variable some linguistic variables are defined. The relation between independent and linguistic variables is defined by Fuzzy sets indeed. (Yen and Langari, 1999). Table 3 shows an example of fuzzy rules:

**Table 3.** An example of fuzzy rules

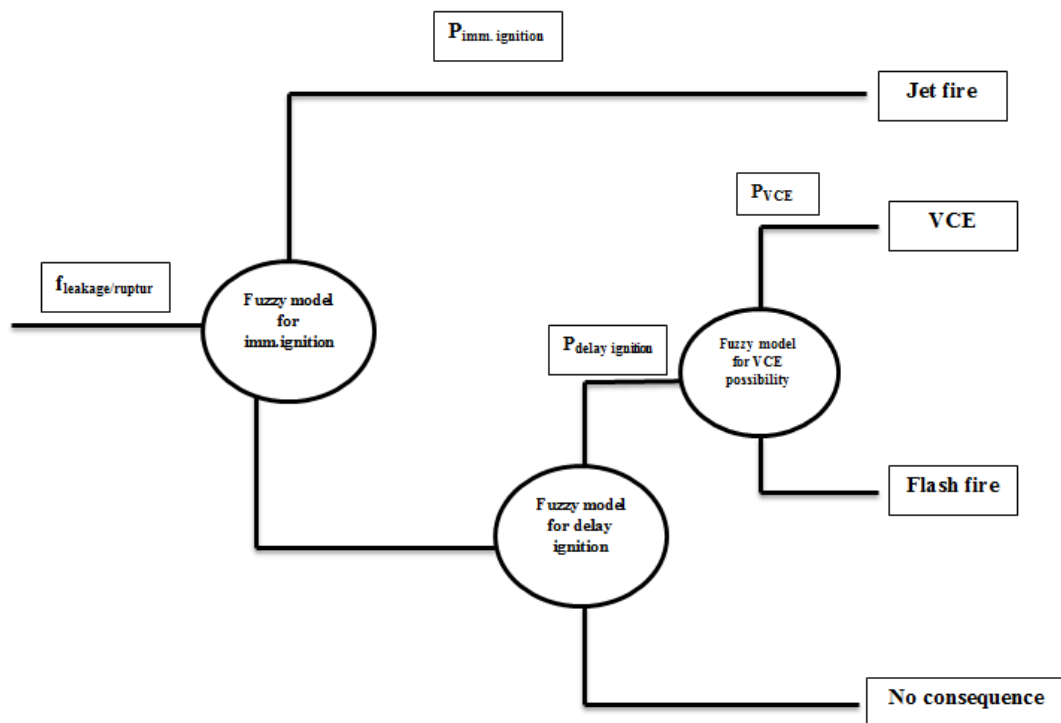
	Very low	Low	medium	High	Very high
Auto ignition temperature				×	
Release rate			×		
Minimum ignition energy					×
Possibility of immediate ignition				×	

After the calculation of Fuzzy output according to the Fuzzy sets and Fuzzy rules, a so-called defuzzification process must be performed and fuzzy conclusions have to be converted to crisp. For this purpose there are different defuzzification techniques. In this study Area Centroid is proposed for defuzzification as it is common in Fuzzy risk assessment studies such as the work of Markowski and Mannan, 2008.

The Area Centroid calculates the weight average of output fuzzy set (Kaufmann and Gupta, 1985). (equation 7):

$$\text{crisp output} = \frac{\sum_{i=1}^{n_x} x_i \mu(x_i)}{\sum_{i=1}^{n_x} \mu(x_i)} \quad (7)$$

In this paper, Fuzzy functions are built for each of the factors affecting the calculations of event tree, including immediate ignition, delayed ignition and VCE occurrence possibility. The input variables to these functions are Fuzzy sets and their outputs would be the possibility of every chain of events. As mentioned before the term possibility is used instead of probability as the probability of an event in a variety of experimental conditions tends to unity. In this case, however, since the expert opinion is included, various possibilities can be achieved based on different experts and situations. Also, the different parameters of Fuzzy sets, including the shape and type of sets, are considered as the flexible power of the model and the expert opinion can affect the structure of these parameters (Fuzzy sets). Figure 3 shows the scheme of the proposed model.



**Figure 3.** Proposed event tree for flammable chemicals release

### 3.2 Possibility of immediate ignition

Analysis of past accidents, the theory of immediate ignition and expert's opinion indicate that three main parameters influencing immediate ignition occurrence are: Minimum Ignition Energy (MIE), Auto Ignition Temperature (AIT) and rate of material release (Crowl and Louvar, 2001). Possibility of immediate ignition is more influenced by chemical properties and rate of release rather than the conditions of the surrounding environment of release.

#### 3.2.1 Minimum ignition energy (MIE)

The minimum ignition energy (MIE) is the minimum energy required to initiate a combustion reaction. Lower values of MIE means the chemical will catch fire easier. So it is more probable for a chemical having low MIE to find a source of immediate ignition. Many of the hydrocarbons have MIE between 0 to 1 mJ. So in this study and for fuzzification of this variable, the energy

range of 0 to 2 mJ has been divided into four categories of very low, low, medium and high quality.

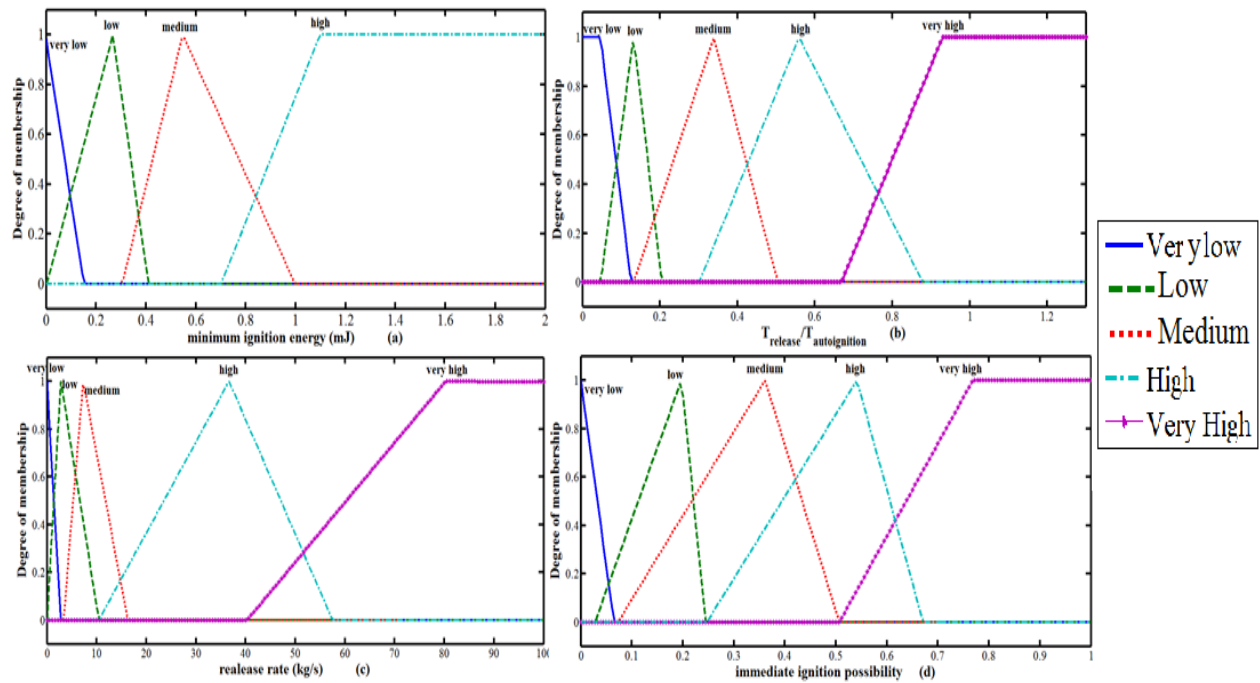
### **3.2.2 Auto Ignition Temperature (AIT)**

The lowest temperature at which the material itself provides the energy required for ignition is called AIT. Having lower AIT means a certain chemical is more flammable. For taking into account the effect of AIT on the possibility of immediate ignition, a new variable is defined in this study. This variable is the ratio of discharge temperature of the released material to AIT of that chemical. Based on expert's opinion, and for enabling fuzzification, a range from 0 to 1.3 for this variable has been divided into five categories of very low, low, medium, high and very high.

### **3.2.3 Material Release Rate**

Based on past accident analysis many of the VCEs happened in process industries started with a gasket failure or pipe leakage. Higher rates of chemical release will lead to higher chances of immediate ignition. So release rate is selected as one of the influencing parameters on the immediate ignition possibility. This variable in the range of 0 to 100 kg/s has been divided into five categories of very low, low, medium, high and very high.

Figure 4 shows the fuzzification and formation of Fuzzy sets for variables influencing the possibility of immediate ignition.



**Figure 4.** Fuzzy functions for minimum ignition energy (a), ratio of release temperature to auto ignition temperature (b), release rate (c) and immediate ignition possibility (d)

Based on past data and experience, Bevi (2009) has provided a table in which the likelihood of instantaneous ignition occurrence probability based on material release rate and flammability, has been identified (Table 4).

**Table 4.** Probability of immediate ignition for various condition (Bevi, 2009)

Substance category	WMS category	Source term	Probability of Immediate ignition
Category 0 Average/high reactivity	Extremely flammable	<10 kg/s	0.2
		10-100 kg/s	0.5
		>100 kg/s	0.7
Category 0 Low reactivity	Extremely flammable	<10 kg/s	0.02
		10-100 kg/s	0.04
		>100 kg/s	0.09
Category 1	Highly flammable	All flow rates	0.065
Category 2	Flammable	All flow rates	0.01

Category 3,4		All flow rates	0
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### **3.4 Possibility of delayed ignition**

By analyzing the past accidents in which a delayed ignition led to a VCE, some key factors have been revealed to have more influence. The main factors that affect the occurrence possibility of delayed ignition are: Chemical Flammability Limits, Area classification and material release rate.

#### **3.4.1 Flammability limits**

Any flammable substance is combustible only if the fuel to air ratio falls inside a certain range which is called 'Flammability limits'. A wider range of Flammability limits for a chemical means, in case of equal release rate, that the chemical forms a bigger cloud having the combustible fuel/air ratio. So the probability of reaching a delayed ignition source would be higher. As the flammability limits of many hydrocarbons range from 0 to 70 percent, in fuzzification this range has been selected and divided based on expert's opinion into the five categories very low, low, medium, high and very high.

#### **3.4.2 Material Release rate**

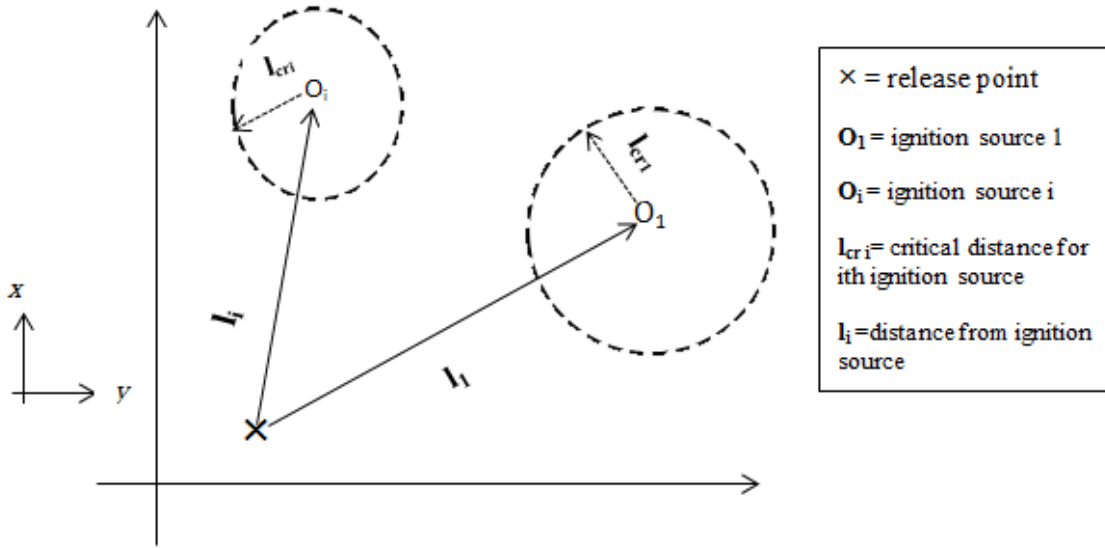
For a certain chemical, a larger release rate will lead to the formation of a larger flammable cloud and hence a higher chance of finding a delayed ignition source. Again based on expert's opinion, a range between 0 and 100 kg/s is used and divided into five categories in fuzzification.

#### **3.4.3 Area classification**

The existence of ignition sources in an environment can have a significant effect on the possibility of ignition occurrence. Therefore, the environment in which the release occurred can be divided qualitatively into three categories of low-, medium- and high risk. Hence, we define an index by which it is possible to determine the degree of environmental risk. According to Figure 5, it can be said that three factors such as type, number of ignition sources and their

distances from the release point are effective in determining the degree of environmental risk. Due to the factors indicated, the index can be defined as follows:

$$w'_i = \begin{cases} \left( \frac{w_i}{\left( \frac{l_i - l_{cri}}{l_{cri}} \right)} \right) & \text{if } l_i > l_{cri} \\ w_i & \text{if } l_i < l_{cri} \end{cases} \quad index_{ignition\ source} = \max(w'_i) \quad (8)$$



**Figure 5.** effect of type, number and distance from release point of ignition sources on ignition source index ( $w'$ )

All types of ignition sources are not equal in their sparking ability (Uijt de Haag and Ale, 2005). In equation 8,  $w_i$  is the weight being assigned to any of the ignition sources, based on the amount of its influence on the delayed ignition, while  $w'_i$  is the modified weight according to the distance from release point and  $l_{cri}$  is the critical distance which before this distance, the potential weight of each ignition source is constant and at its maximum value. So before this critical distance the potential weight of each ignition source is not decreased with increasing of the distance from release source. These critical distances are dependent to the type of ignition sources.

Table 5 shows the weight types and critical distance for sources of ignition. One of the main advantages of this index is considering the distance of spark source from release point, which has



not been seen in previous studies. In Table 6, an historical review of VCE events, with regard to spark sources, is shown (Koshy et al, 1995).

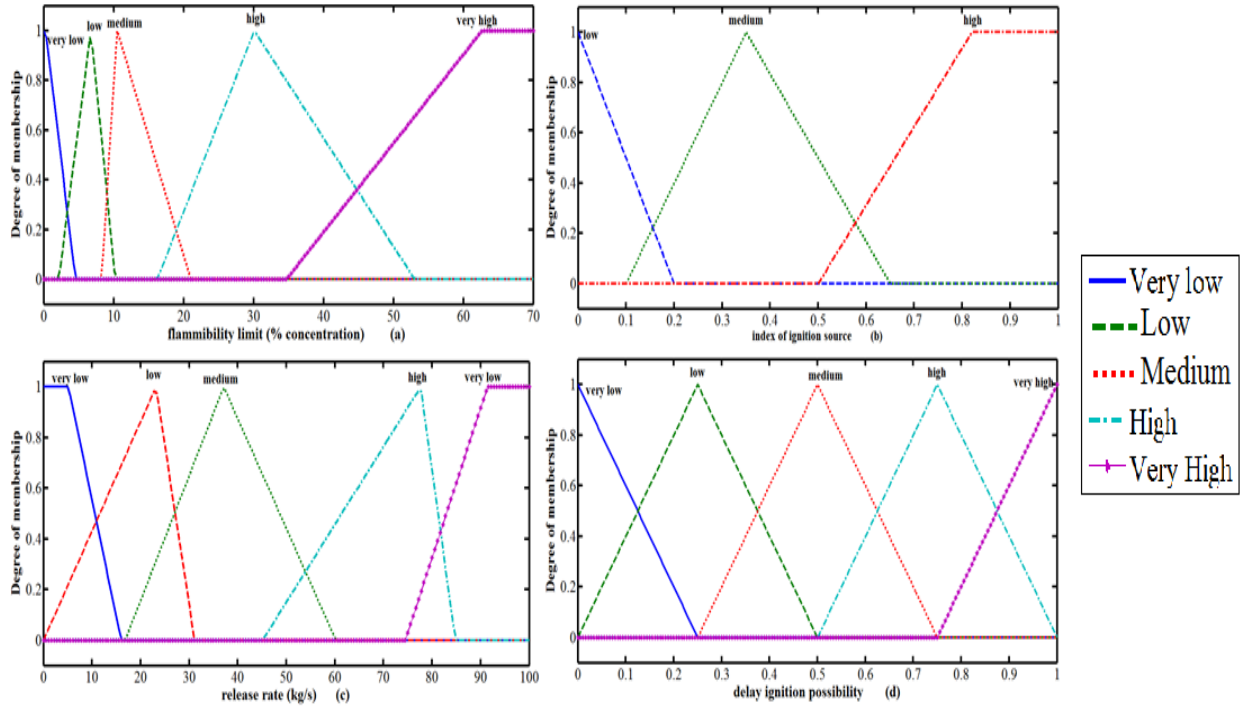
**Table 5.** Potential weight and critical distance for various ignition source type

Ignition source type	Ignition Potential weight( $w_i$ )	Critical distance( $l_{cri}$ ) m
Flare	1	120
Furnace	0.9	100
Boiler	0.6	80
Heat exchanger	0.4	50
Motor vehicles	0.3	25
Other	0.1	15

**Table 6.** Historical review of vapor cloud explosion incidents in presence of ignition sources  
(Koshy et al, 1995)

VCE incident	Ignition source	Distance from release point(m)
Abqaiq, Saudi Arabia	Flare (low level)	460
Commerce city, USA	Heater	40
Enschede, the Netherlands	Heater	Near by
Pampa, USA	Boiler	50
Baton Rouge, USA	Furnace	300

Figure 6 shows the Fuzzy functions of variables and the occurrence possibility of delayed ignition.



**Figure 6.** Fuzzy functions for flammability limit (a), ignition source index (b), release rate (c) and delayed ignition possibility (d)

### 3.5 Possibility of VCE rather than VCF:

Material release rate, burning velocity, and congestion of the surrounding environment, play the most important roles in determining the occurrence possibility of VCE rather than VCF in a plant. Past accident reports show that 80% of VCEs happened in confined areas (Wiekema, 1984).

#### 3.5.1 Material Release rate

The material release rate has a significant role in determination of the possibility of a VCE occurrence. In higher release rates in addition to more chaos in the release area, higher flammable gas inventories would be available favoring VCE occurrence.

#### 3.5.2 Burning velocity

Based on previous studies (AIChE/CCPS,1994; Lees,1996). one of the most important factors in VCE occurrence is chemical reactivity. But there is not a specific criterion to measure chemical reactivity regarding combustion reaction. In this study, Burning velocity is considered as a measure of chemical reactivity. Burning velocity is an inherent property of flammable material mixture that affects the rate of a burning reaction (Dahoe, 2005). Table 7 shows burning velocity ( $S_u$ ) for some materials.

**Table 7.** Burning velocities of selected substances in air and oxygen (Lees,1996)

Material	$S_u(\text{cm s}^{-1})$
<u>In air</u>	
Methane	36.4
Ethane	40.1
Propane	45
n-Butane	40.5
n-Hexane	38.5
Ethylene	68.8
Town gas	-
Acetylene	173
Hydrogen	320
Benzene	40.7
<u>In oxygen</u>	
Methane	393
Propane	390
Ethylene	550
Acetylene	1140
Hydrogen	1175

Higher values of Burning velocity lead to a higher likelihood of VCE compared with VCF. To fuzzifying this parameter, three qualitative sets can be categorized in the range of 0 to 300 cm/s.

### 3.5.3 Plant Congestion

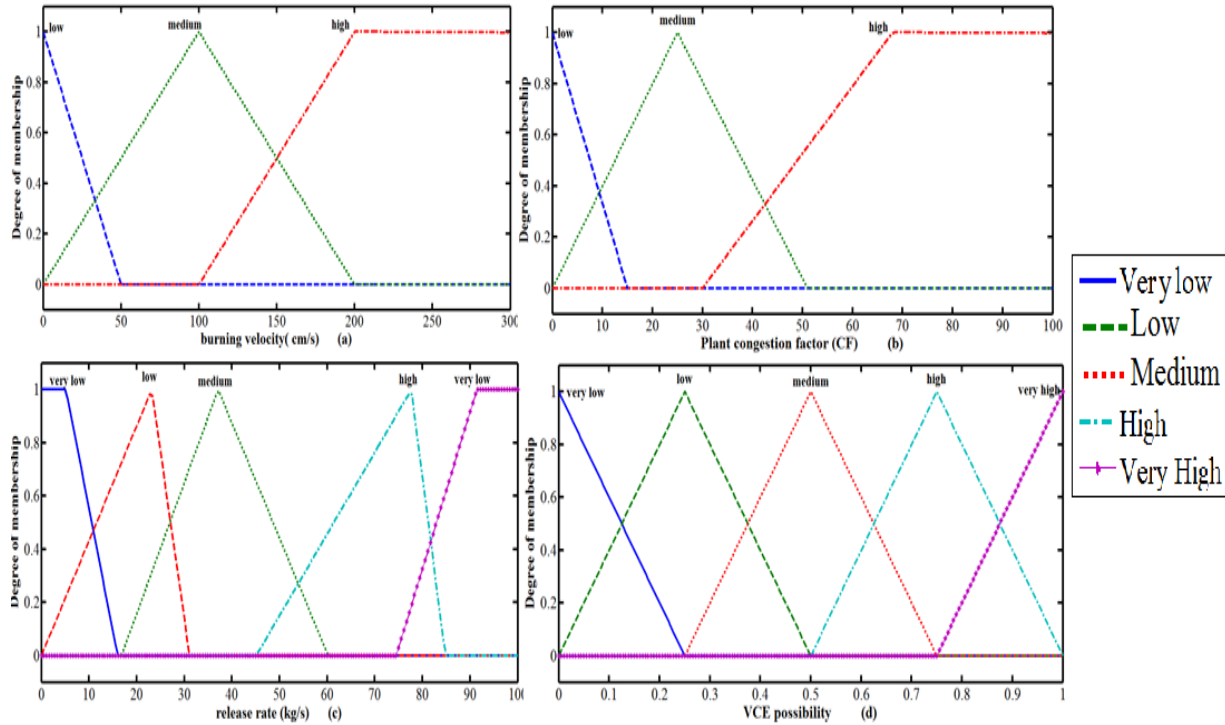
Turbulence in the released cloud would increase the chance of VCE occurrence rather than VCF. One of the most important factors in creating chaos in the released vapor cloud is the plant congestion due to the arrangement of piping structure and other equipment. To quantify the plant congestion, a new parameter is introduced in this paper. Plant Congestion Factor is defined as the

percentage of total space filled by the equipment and piping over total space of release environment as follows (Eq. 9).

$$CF = \frac{\text{volume filled with pipe and equipment}}{\text{total volume of release location}} \quad (10)$$

Based on expert's opinion, this parameter can be divided qualitatively into three categories of low density, medium density and high density in the range of 0 to 100.

Figure 7 shows the different Fuzzy functions and the occurrence possibility of VCE rather than VCF.



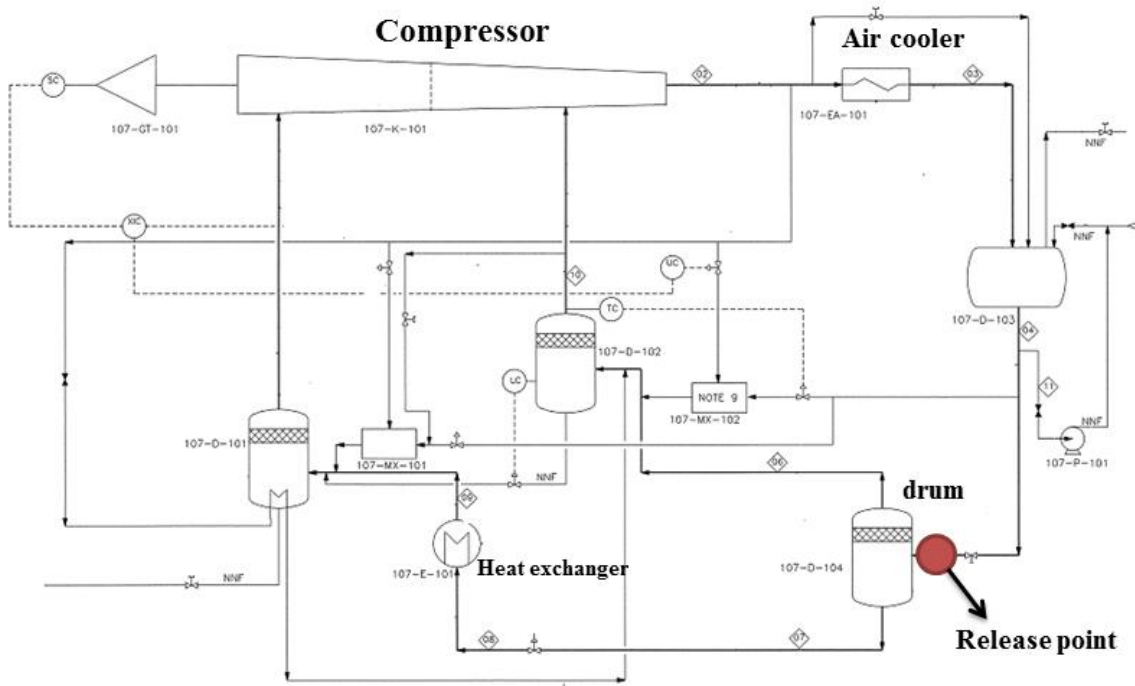
**Figure 7.** Fuzzy functions for burning velocity (a), Plant Congestion factor (CF) (b), release rate (c) and VCE occurrences possibility (d)

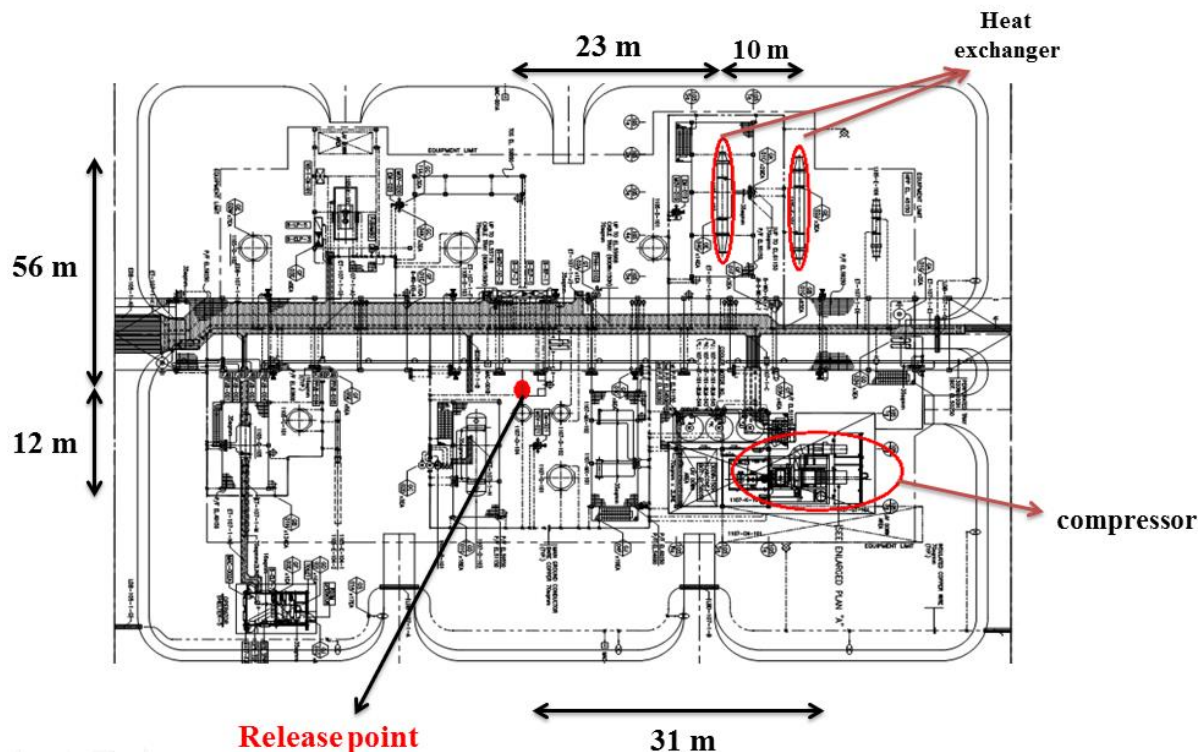
#### 4. Case study

To show the applicability and advantages of the new proposed method, a case study has been performed. A refrigeration cycle due to its importance in many hydrocarbon processing plants

and inherent hazards, has been selected as the case under study. In this cycle, a refrigerant is used to absorb heat from a cold environment and transfer to a warm environment. Compressor, condenser, evaporator and pressure valve and two-phase separators are known as the key components of such cycles. Refrigerant enters the compressor as a saturated vapor and its temperature and pressure are increased. In this higher pressure, hot refrigerant is cooled in the condenser and becomes saturated liquid. Then the refrigerant pressure suddenly drops passing through a valve, and this leads to partial evaporation and reduction of its temperature. Thus, the refrigerant at very low temperature absorbs heat from the cool environment by passing through the evaporator and discharges in vapor phase. In this specific case under study, a 98% propane stream is used as the refrigerant and reduces the temperature of the process gas from 8 to -13 °C .

The Process Flow diagram (PFD) and plot plan of this typical unit is shown in Figure 8.





**Figure 8.** Scheme of PFD (a) and Plot Plant (b) of refrigeration unit

The proposed method can be applied for any release scenario and finally to estimate the VCE possibility. In this study, the initial event has been considered to be a medium size leak in the pipe carrying refrigerant upstream of drum D-104 as shown in Figure 8 (b).

In Table 7, refrigerant characteristics and ambient and operational conditions of the unit are given, according to P&ID, layout and mass balance of the unit. Based on piping plans and unit layout Plant Congestion Factor is calculated and tabulated in Table 8. Considering the Area classification in this plant, the ignition source index is also calculated.

**Table 8.** refrigerant characteristics, environmental and operational conditions of refrigeration unit

Material properties	
Refrigerant material	Propane
Normal boiling point( $^{\circ}\text{C}$ )	-42
Release temperature( $^{\circ}\text{C}$ )	-25
Release pressure(barg)	0.8
Release rate( $\text{kg s}^{-1}$ )	55.2

Minimum ignition energy(mJ)	0.25
Auto ignition temperature( $^{\circ}\text{C}$ )	432
Burning velocity( $\text{cm s}^{-1}$ )	45
Flash point( $^{\circ}\text{C}$ )	-104
Flammability limit(%)	7.2
Delayed ignition time (s)	1.3
<b>Environment properties</b>	
Plant Congestion Factor(%)	35
Ignition source index	0.34
Ambient temperature( $^{\circ}\text{C}$ )	40

Other refrigerant rather than Propane can be used in this cycle. The characteristics of some of these refrigerants are given Table 8. According to the simulations done, the mass flow rate corresponding to each of these refrigerants, in order to bring the gas temperature from 8 to  $-13^{\circ}\text{C}$ , is also given the Table 9. In addition to fixed and operating cost in selection of the best refrigerant a key parameter is safety. So in this study a comparison has been done based on the probability of experience a VCE and these refrigerants are compared in this way.

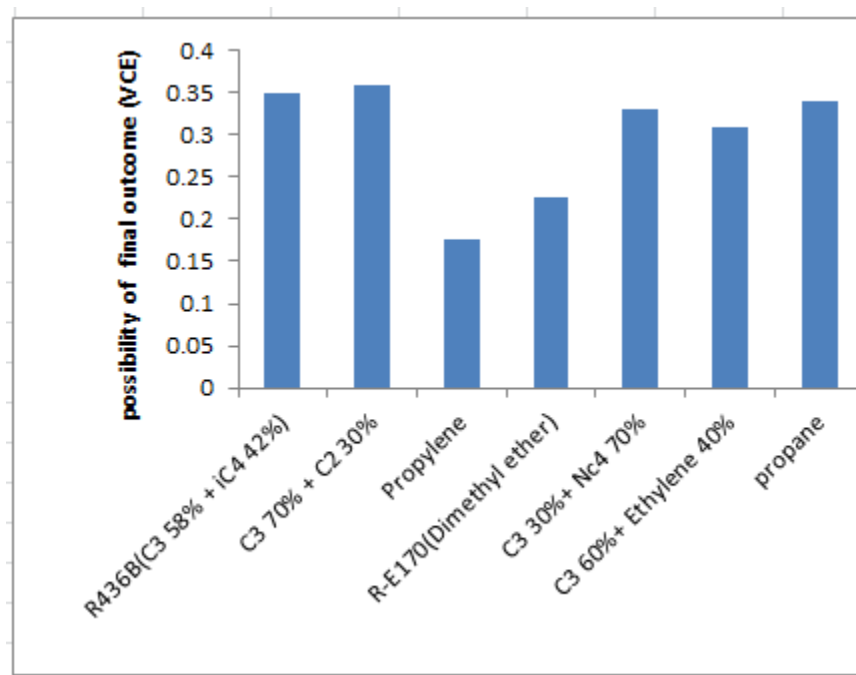
**Table 9.** characteristics of selected refrigerants

	R-436B (C3 58%+iC4 42%)	C3 70% +C2 30%	Propylene	R-E170(Dimethyl ether)	C3 30% + nC4 70 %	C3 60% + Ethylene 40%
Normal boiling point ( $^{\circ}\text{C}$ )	-33.4	-53	-47	-24	-18.1	-66.4
Release pressure (barg)	0.85	0.85	0.82	0.82	0.81	0.91
Minimum ignition energy (mJ)	0.19	0.25	0.28	0.30	0.25	0.14
Auto ignition temperature ( $^{\circ}\text{C}$ )	479	485	458	350	333	510
Burning velocity ( $\text{cm s}^{-1}$ )	42.2	44	40.3	48	44	41
Flash point ( $^{\circ}\text{C}$ )	-95	-111	-108	-41	-87	-118
Flammability limit (%)	7.2	10.3	8	27	6.7	16.8
Release rate ( $\text{kg s}^{-1}$ )	45.3	54.6	37.4	30.2	40.1	61.3

## 5. Result and discussion

In this section Event trees are developed for the estimation of VCE possibility for Propane as the refrigerant and the result is compared with the output of calculation from other existing models.

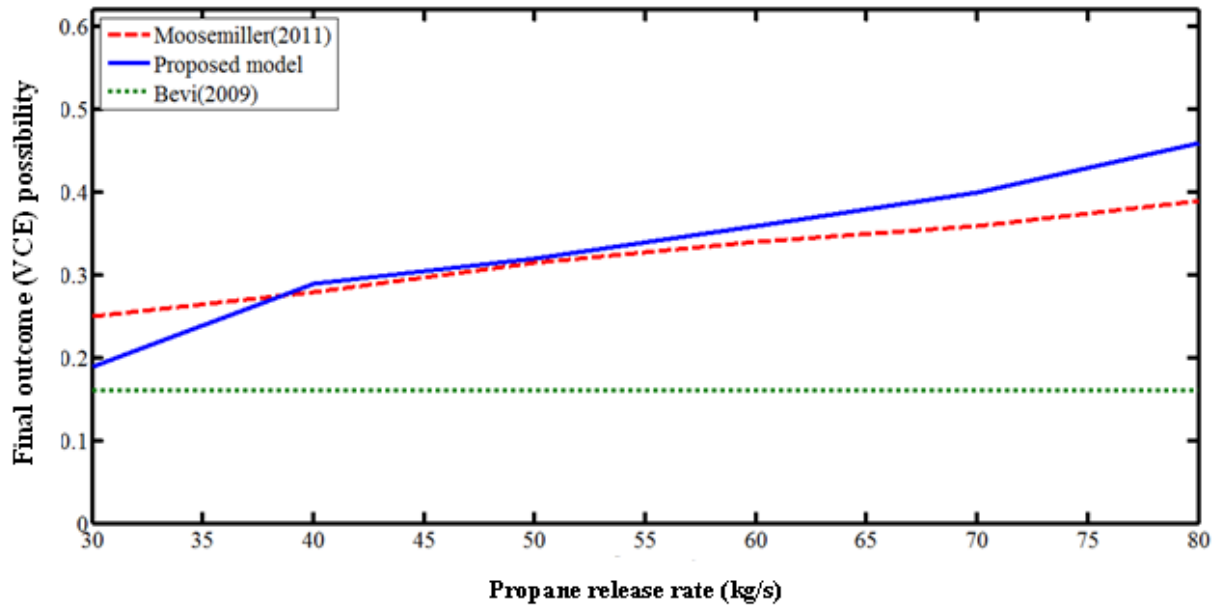
By applying the new proposed method of Fuzzy calculation, the occurrence possibility of VCE for various hazardous materials has been calculated and shown in Figure 9 shows. As can it be seen, the final outcome (VCE) occurrence possibility of propylene and dimethyl ether is lower than the rest of the materials; because the release rate for these two materials is lower than the rest of materials if used in the refrigeration cycle. Also, the release rate of dimethyl ether is lower than propylene, but the final outcome (VCE) occurrence possibility of dimethyl ether is higher; because of the higher flammability potential of the substance. These findings can play a key role in selecting an inherently safer refrigerant to be used in the design phase.



**Figure 9.** possibility of final outcome (VCE) for various refrigerant

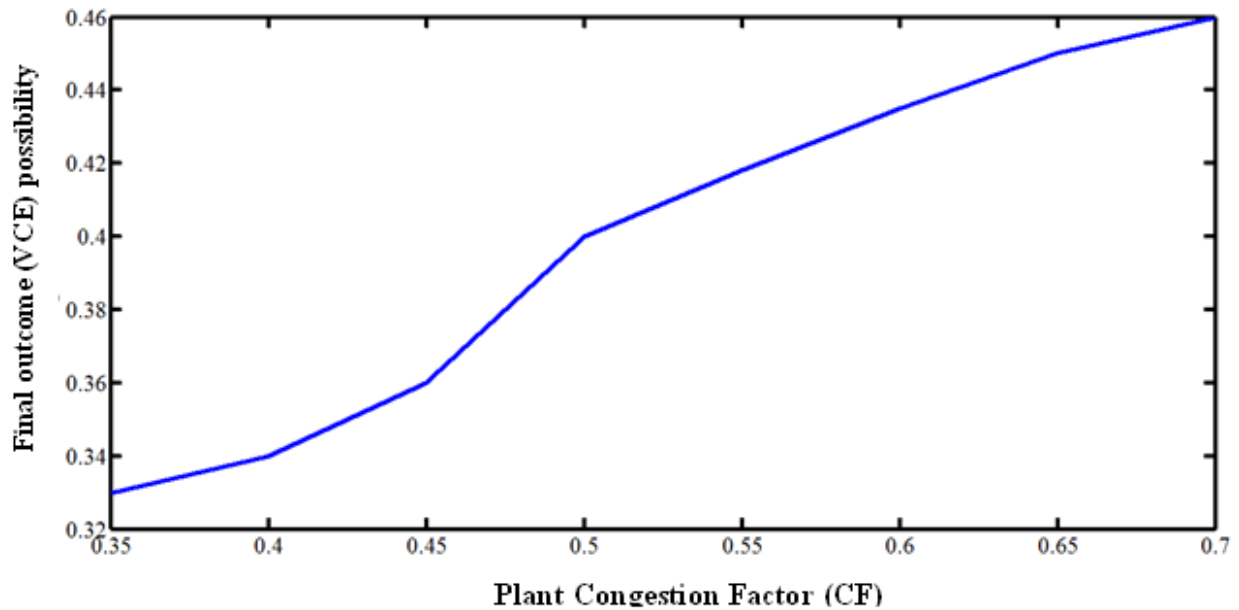
In Figure 10, the effect of the material release rate on VCE possibility is shown. VCE possibility is estimated by the new proposed method and the result is compared with the calculation output of the other existing models. As it was expected, by increasing the release rate, the occurrence possibility of the final outcome (VCE) is increased. It also can be seen that the predicted results have a difference with the results of the Moosemiller (2011) model. It can be seen that the Bevi (2009) model is not sensitive to the material release rate.





**Figure 10.** Effect of release rate on final outcome (VCE) possibility

An important question for risk analysts is how big is the effect of plant congestion on the occurrence possibility of a VCE. As it can be seen in Figure 11, due to an increase in chaos and turbulence in the unit, the VCE possibility is higher in congested plants.



**Figure 11.** effect of Plant Congestion Factor on final outcome (VCE) possibility

Table 9 shows the effect of the spark sources potential index on the occurrence possibility of a VCE, in the case that the flare spark source is present near the release location. For different distances from the release location, the occurrence possibility of the final outcome (that is, a VCE) is specified. According to Table 10 and based on the presented model, it is observed that the existence of a spark source, such as a flare, may sometimes double the final outcome (VCE) occurrence possibility, which certainly demonstrates the importance of spark sources and also their distances from release point.

**Table 10.** distance effect of spark source(Flare) on final outcome (VCE) possibility

Flare distance from release point(m)	Final outcome(VCE) possibility
60	0.54
140	0.48
300	0.41
450	0.37
No flare	0.29

## 6. Conclusions

The estimation of VCE occurrence possibility as a very frequent and destructive accident among the process accidents is a necessary part of any QRA study. Conventional estimation of VCE possibility is done by developing an Event tree. But in specifying probabilities, in each branch there are certain uncertainties and existing guidelines and models not being taken into account. These deficiencies make one of the most important calculations in a QRA study, unreliable. To overcome these deficiencies, a new method is proposed in this paper for VCE possibility estimation that not only benefits from the strengths of Fuzzy theory but also considers all the major influencing parameters in specifying the probabilities of each Event tree branch. Parameters such as plant congestion, material release rate and nature of released chemical are considered while specifying immediate/delayed ignition and VCE/VCF possibilities.

Applicability and advantages of this new proposed model is shown by applying it to estimate VCE possibility in a Refrigeration Cycle. The results are compared to the results of the method currently employed. A sensitivity analysis has also been done to study the effect of different parameters in the final value of VCE possibility.

## Nomenclature

$A$	Time constant ( $s^{-1}$ )
$CF$	Plant Congestion Factor
$E$	Apparent activated energy(J)
$f_{\text{leakage/rupture}}$	Leakage/rupture frequency ( $\text{year}^{-1}$ )
$K$	Strength constant
$LFL$	Lower flammability limit (% concentration of flammable material in air)
$l_i$	Distance of $i^{\text{th}}$ ignition source from release point
$MIE$	Minimum ignition energy (mJ)
$M$	Continues Release rate ( $\text{kg s}^{-1}$ )
$N$	Number of release source
$P_i$	Probability of $i^{\text{th}}$ incident
$P$	Pressure(psig)
$P'_i$	possibility of $i^{\text{th}}$ incident
$S_u$	Burning velocity( $\text{cm s}^{-1}$ )
$UFL$	Upper flammability limit(% concentration of flammable material in air)
$T$	temperature(C)
$T$	time (s)
$w_i$	Potential weight of ignition source

### Greek letters

$\mu$	Degree of membership
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